From AdA to ACO

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LAL 98-103
December 1998

Laboratoire de l'Accélérateur Linéaire

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Reminiscences of Bruno Touschek

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Talk given at the Bruno Touschek Symposium
Frascati, 16 November 1998

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de Physique Nucléaire
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ABSTRACT

Soon after Bruno Touschek had proposed to store electrons and positrons in a single circular accelerator in order to study their mutual annihilations, the small 'AdA' ring was designed and built by a team from the Frascati National Laboratory. AdA played an important role as a prototype for larger e^+- e^- machines, such as ACO and ADONE. The following is an informal account of the years when the ring operated at the Laboratoire de l'Accélérateur Linéaire. During these years, Bruno Touschek and his Italian colleagues used to commute regularly between Rome or Naples and Orsay to carry out measurements with AdA, within a Franco-Italian collaboration.

1 The invitation to bring AdA to Orsay

This story begins in the spring of 1962. Following a visit to the Frascati Laboratory, Pierre Marin suggested to the Director of the Laboratoire de l'Accélérateur Linéaire, André Blanc-Lapierre, to invite the Italian team which had designed and constructed the AdA ring [1] and had performed a first series of experiments with it at Frascati, to bring the ring to Orsay where it could get a second wind thanks to the intense, low emittance beam of the linear accelerator. To initiate a Franco-Italian collaboration, A. Blanc-Lapierre invited Bruno Touschek to give a seminar at Orsay in May of that year (1962).

Some weeks later, when AdA was transported from Frascati to Orsay and went through the French customs, the accompanying scientists were asked what was in the ring. The answer given was 'vacuum'. This obviously did not satisfy the customs officer who insisted that the ring be opened so that he could scrutinize this vacuum. It took the intervention of Francis Perrin, then the Haut Commissaire à l'Energie Atomique, to get over this hurdle. I do not know whether our Italian colleagues were impressed by the high degree of professionalism displayed by the French customs, but I suppose that they appreciated the fact that, when necessary, the LAL Directorate had access to the highest national authority in nuclear physics.

AdA was greeted at Orsay by a small team composed of Pierre Marin and François Lacoste. Pierre Marin remembers quite vividly an incident which marked the installation of AdA and which could have turned out to be a dramatic one. The experimental hall where AdA was to operate was an intermediate energy hall, equipped with a special roof comprising a few water tanks having the shape of very large rectangular boxes which provided the proper radiation shielding. They could be moved horizontally in order to make room for a crane located above them. In the course of the AdA installation, it happened that, while the mechanical device used to support the ring was hanging on the crane hook, someone pressed a button which started the motion of the water tanks. These tanks were so heavy that when they reached the crane cable they just pulled the crane together with the AdA support. A member of the Italian team saw that the AdA support was heading towards a wall and screamed out. Thus alerted, Pierre Marin was able to run and stop the water tanks just in time to avoid a catastrophe.

By August 1962, the storage ring was installed at Orsay. At that time, François Lacoste was about to leave the laboratory to work in one of his family's scientific firms, and so André Blanc-Lapierre asked me to replace him and work with Pierre Marin.

I finished the military service in the fall of that year. Before that, I had spent two years at the High Energy Physics Laboratory of Stanford where I had watched people like Bernie Gittelman, Jerry O'Neill and Burt Richter install an electron-electron storage ring [2] in a hall close to the place where I was working. This installation was not completed when I left Stanford.

2 The Italian team and its commuting to Orsay

Once AdA was installed at the Laboratoire de l'Accélérateur Linéaire, the Italian team used to come every other weekend (at certain times every weekend) to take data. All would come by plane, except Bruno Touschek who preferred traveling by train. At that time the quality of the meals served on the train running between Rome and Paris warranted the extra traveling time. Guiseppe Di Giugno would come a few days ahead of the others as he was in charge of implementing whatever modifications had been thought of between two runs. At times Pierre Marin and myself would help him do this.

Each one of the Italian team members had his own personality. Concerning Bruno Touschek, one was immediately struck by his intelligence and wit. He was very imaginative and his way of dealing with physics issues was always very elegant. In very good spirits most of the time, he could also be quite critical in some instances. The head of the Italian group was R. Querzoli. He was the most senior physicist of the group and was quite good at playing the role of moderator when difficulties or excitement reached high levels. I enjoyed particularly working with G. Di Giugno, the youngest member of the Italian team, who showed a lot of ingenuity in improving the electronics of the detector.

3 The prospects of storage ring physics with AdA

AdA was a wonderful instrument (Fig. 1), small enough to be thought of as a table-top apparatus. With it, one could dream of producing electron-positron annihilations into muon pairs or pion pairs. That remained a dream, but AdA allowed us to tackle a number of fundamental aspects of storage ring physics which were unexplored at the time. Nothing had been experimentally tested previously as far as the behaviour of stored beams was concerned. The actual size of the particle bunches had not been measured, beam lifetimes had not been checked and whether opposite beams did encounter each other or not was an open question. Clearly these were very important points to be investigated with AdA which played the role of an $e^+ - e^-$ storage ring prototype.

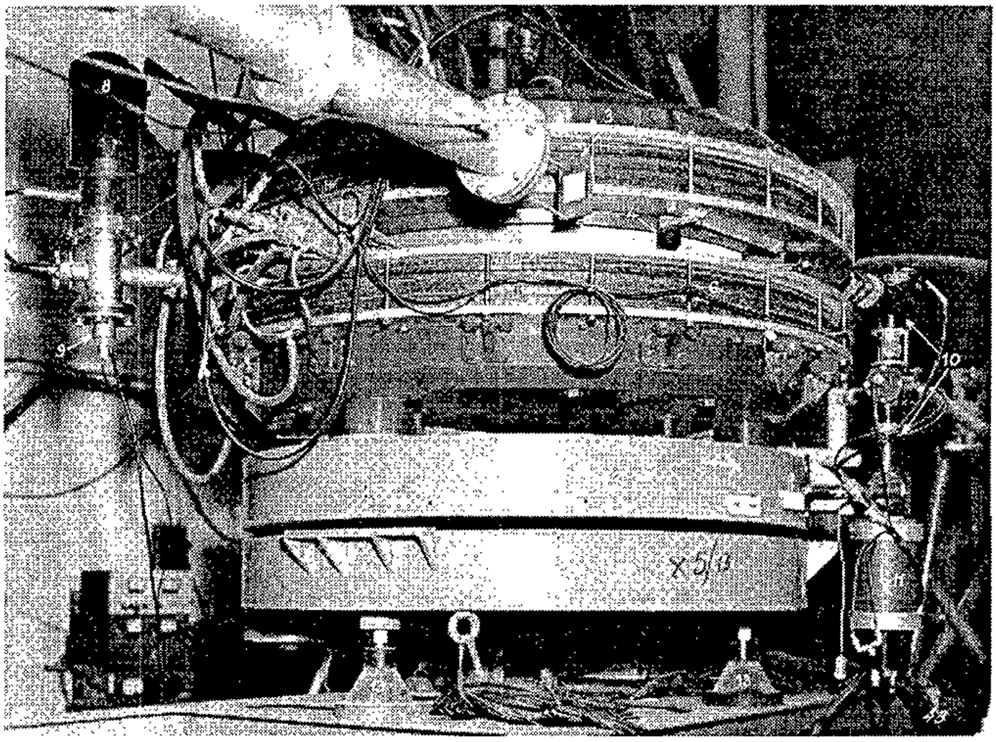


Figure 1 : Photograph of AdA taken in 1964 at the Laboratoire de l'Accélérateur Linéaire d'Orsay.

4 The run routine

In practice, to reach these goals, one had to work hard! (See Fig. 2 a.) In order to get the best possible Linac beam conditions, the AdA runs were scheduled during whole week-ends.

Before each run, P. Marin and I would prepare the Linac beam transport. Since we (Pierre and I) ensured the connection with the engineers and operators running the Linac, at least one of us had to stay awake all the time from Friday morning until the next Monday morning.

As a rule, filling the ring was quite a tedious affair, sometimes a laborious one (Fig. 2 b). Some tricks had been imagined to speed up the process, like modulating the RF voltage. This amplitude modulation had to be optimized frequently. Furthermore, one had to keep an eye on the RF generator tuning which fed energy to the particles stored in the ring.

21- Dic- 62 - Sabato

~~È stato~~

Questo è il turno in cui per la prima volta

proveremo i 28. Ruggero Querzoli

Giuseppe Di Giugno

Mentre il popolo strombazza io faccio le notti - CB.

(a)

Mettiti sulla riva | di un linac
| d'ecun.

e aspetta che carichi l'anello

del tuo nemico.

Carlo Bernardini 1962

(b)

(1) Observation of single electrons with the electron counter.
HV = 1800, dark current at the beginning of the measurement 40 nA.
We observe the decay of 20 electrons:
from ~~245 nA~~ 222 nA to 176 nA
∴ 46 nA / 20 electrons. 2.3 nA/electron
1 μA = 435 electrons.

(2) 1st attenuation. We accumulate a current of 1.46 μA. The dark current is 0.054 μA the effective current therefore 1.406 μA corresponding to 1.406 × 435 = 611 electrons.
The ~~HV~~ voltage is changed to 1480 volts.
We read 0.146 μA. Dark current 0.024 nA & therefore 0.122 μA effective. This gives 611 : 0.122 = 5.01 × 10³ electrons/μA.

(3) 2nd attenuation. A current of 2.215 μA is accumulated. This corresponds to 2.215 − 0.024 = = 2.191 μA = 1.096 × 10⁴ electrons.
Voltage changed to 1220 volts. Current ~~2.2~~ 0.221 μA ; dark current 0.018. Effective current 0.203 μA. This gives 1.096 × 10⁴ : 0.203 = 5.4 × 10⁴ electrons/μA.

(4) 3rd attenuation. Current of 1.15 μA accumulated ≃ 1.13 μA = 6.11 × 10⁴ electrons.
At 1000 volts 0.115 μA ; dark current 0.015
∴ 0.100 μA effective. Efficiency
6.11 × 10⁵ electrons/μA

(c)

Figure 2 : Three excerpts from the AdA logbook. (a) R. Querzoli's, Di Giugno's and C. Bernardini's handwritings or signatures. (b) C. Bernardini's handwriting. (c) B. Touschek's handwriting.

This watch had to be kept all the time while particles were being stored in AdA. B. Touschek used to follow quite closely the progress of the runs (Fig. 2 c). As a theorist, he did not interfere with the practical actions on the ground. In fact, his attitude was rather conservative as far as turning knobs was concerned. He would insist on not touching anything as long as an intervention was not mandatory. Usually he was rather unsatisfied with the Linac beam quality. With a stopwatch in his hand he would monitor the filling rate and show Pierre Marin and I the results of the statistics he had obtained during the last hour about the beam performance, and let us know that something had to be done to boost it. Never since then have I spent so much time in the linac control room and in the klystron hall to encourage the accelerator engineers and technicians to do whatever could be done to increase the beam intensity.

At the beginning of each AdA run, one had to calibrate the device used to determine how many electrons or positrons were stored during the subsequent hours. Measuring the flux of synchrotron light was a procedure which gave a good perception of physics with this unique mix of macro and micro-physics since, in the end, one could measure the light flux originating in a single electron orbiting around a circle one meter in diameter (Fig. 3).

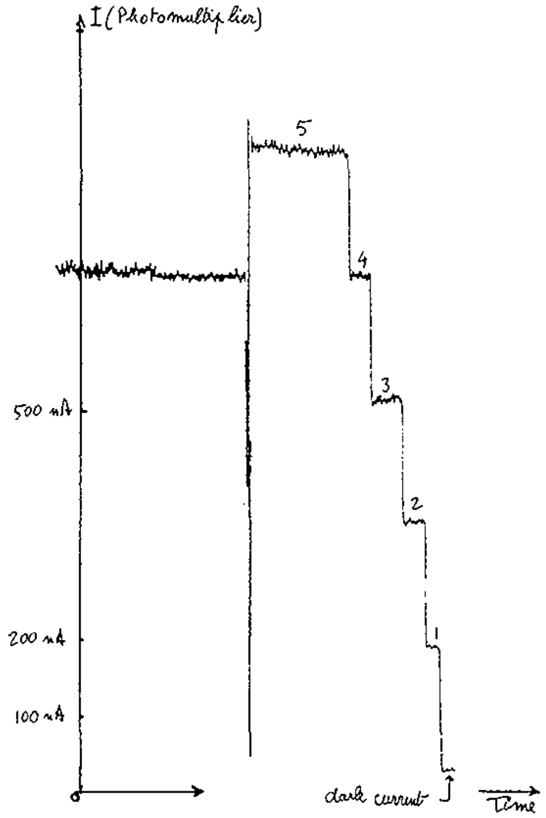


Figure 3 : Signal provided by a photomultiplier detecting the synchrotron radiation emitted by a few electrons stored in the AdA ring.

During such a weekend run, more often than not the Linac or some other device would fail and the filling had to be resumed. B. Touschek's patience was somewhat strained in such circumstances.

On the Monday morning, the conclusions of the run were discussed at the 'Café de la gare' near the Orsay metro station. We would order a substantial breakfast and a good bottle of wine. Depending on the current issues, a second bottle was sometimes ordered and then our discussions dragged on despite the fact that most of us were exhausted.

One of the difficulties met during the first months of AdA's running at Orsay was keeping the first stored beam when the ring was flipped over like a pancake in order to proceed with the injection of the second beam. Quite often the stored beam was lost during this process. The hypothesis was made that magnetic dust would stick to the vacuum chamber wall for a while and would then fall because of gravity, crossing unluckily the orbit of the stored particles, thus 'killing' them all. Having AdA perform some kind of a dance during this flip operation in the hope that the tiny magnetic particles would slide and remain in contact with the vacuum chamber wall did not solve the problem. Thus it turned out that the declaration to the customs officer was not totally true: the AdA vacuum chamber contained not only vacuum but also dust particles.

Then the Italian group came forth with an elegant solution to this dust problem, which consisted in performing a mirror symmetry of AdA with respect to the vertical plane containing the Linac beam. In practice, this symmetry operation needed a new mechanical support that allowed the ring to rotate around a vertical axis and some rails that allowed a translatory motion of the whole device (Fig. 4). These new mechanical items were constructed in Frascati and brought to Orsay in a remarkably short time.

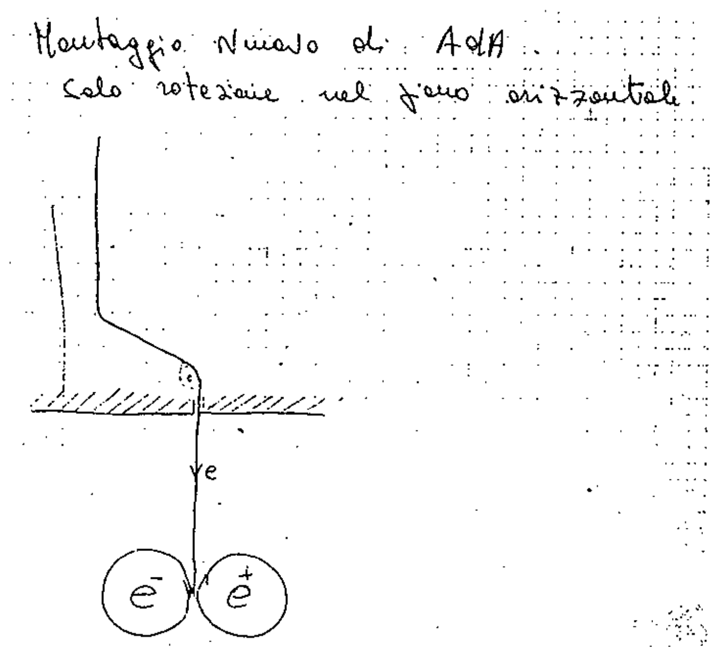


Figure 4: New scheme for injecting alternately electrons and positrons in AdA (Excerpt from the AdA logbook).

5 The first months of data taking and the Touschek effect

As expected, the Linac electron beam allowed one to store both electrons and positrons at a much faster rate than what had been achieved with the Frascati synchrotron. The bad news was the fact that the observed beam lifetime decreased when the number of stored particles increased. At low current, i.e. with less than 10 000 particles stored in AdA, the excellent vacuum maintained in the ring (a few 10^{-10} Torr) was such that a beam lifetime up to 50 hours was observed, while the lifetime dropped to a few hours when $\sim 3\ 10^7$ particles were stored (Fig. 5).

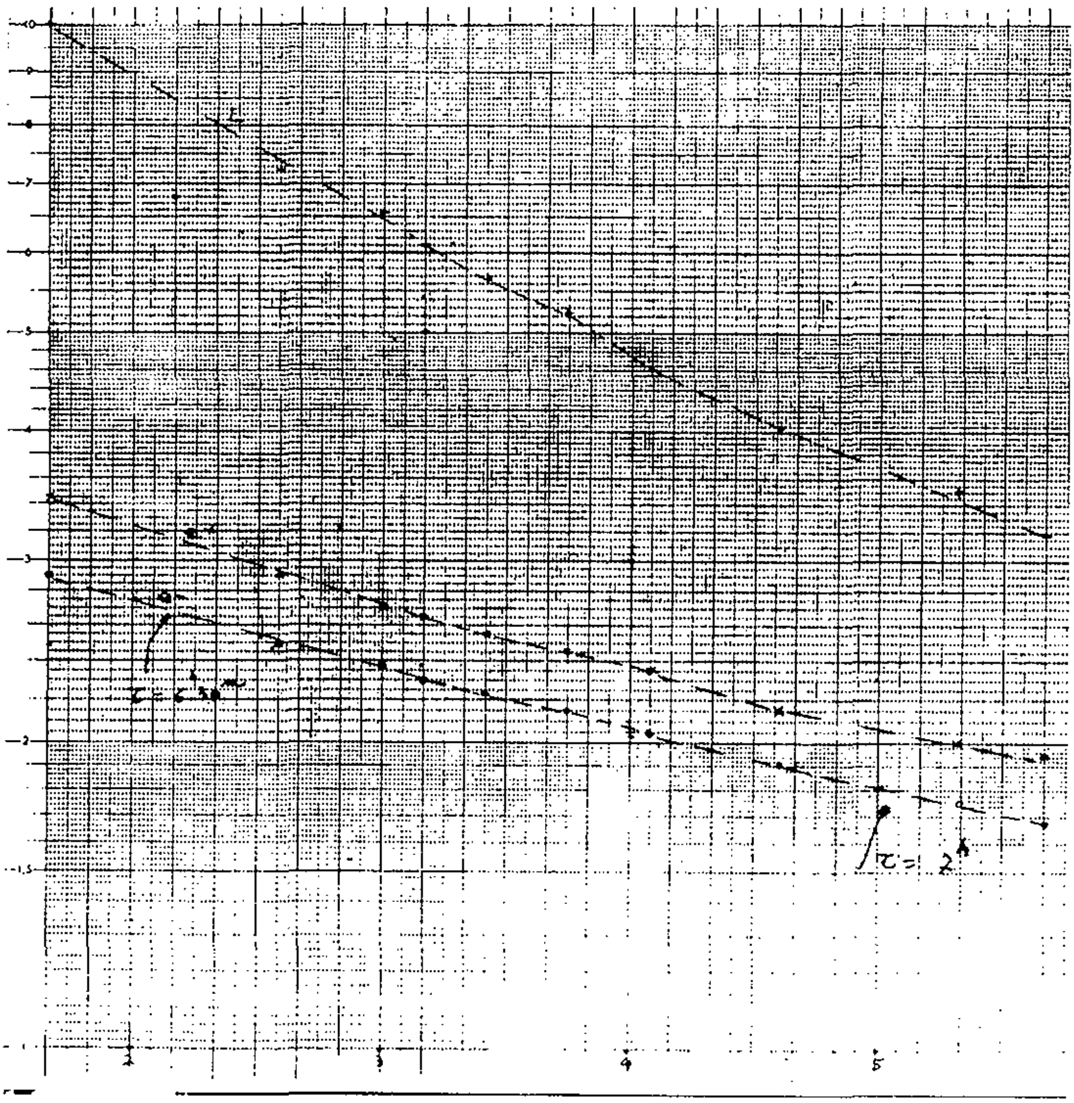


Figure 5: Typical beam intensity and luminosity decay curves when $\sim 10^7$ electrons and positrons were stored in AdA.

A few experimental tests were carried out. The interpretation of this effect was quickly put forth by Bruno Touschek [3] (Fig. 6) on the basis of intrabunch Møller scattering. I remember how this effect was explained to me by Carlo Bernardini in a very pedagogical way.
The 'Touschek effect' is one of those which should be very carefully taken into account when designing storage rings.

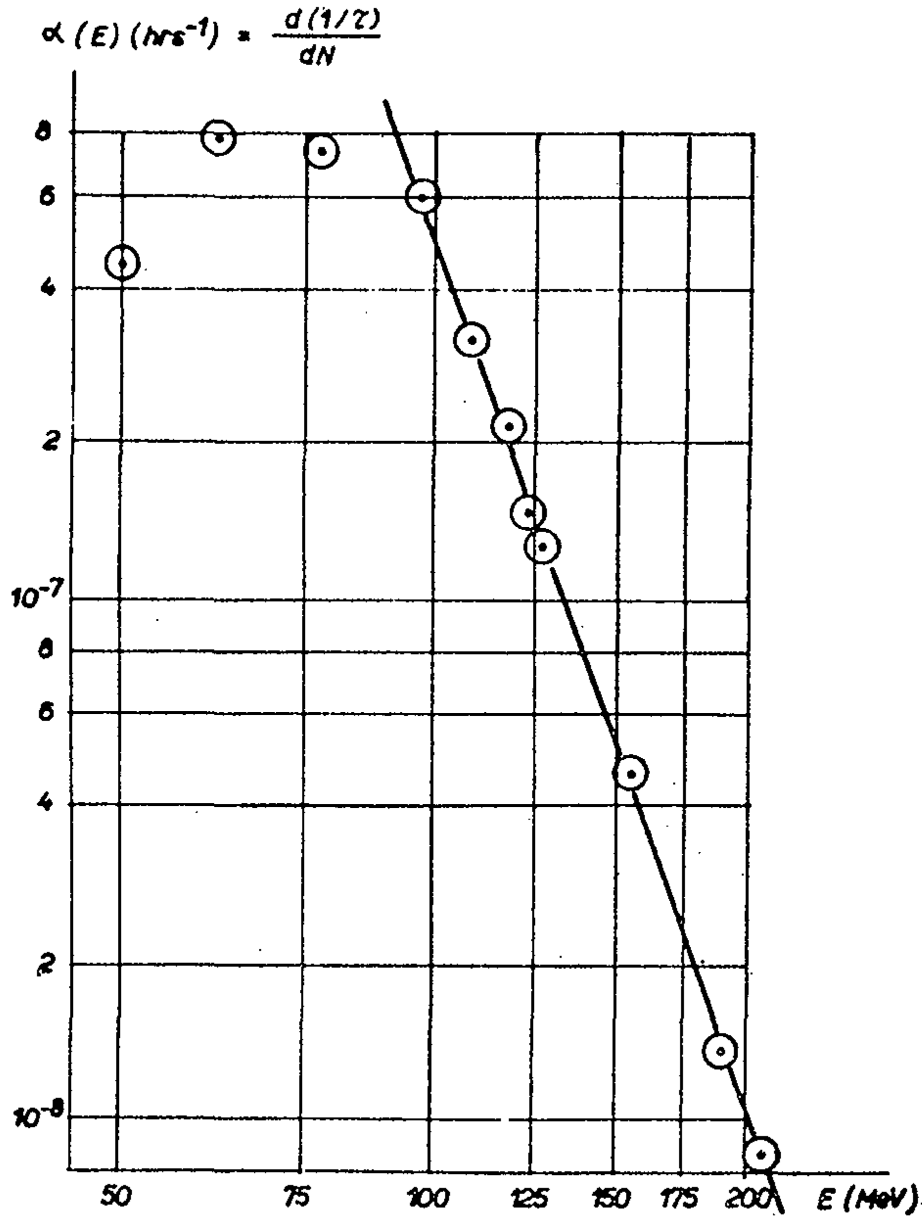
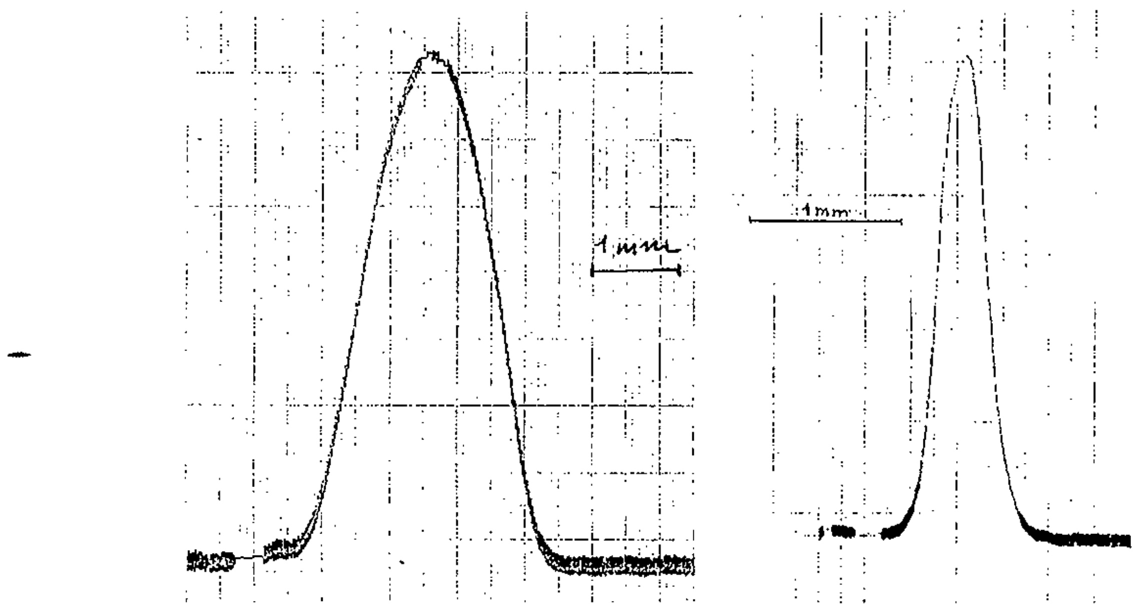


Figure 6: Original Touschek's plot comparing experimental data his own theoretical predictions.

At the time, this effect prevented us from storing as many electrons and positrons as we would have liked, and it brought evidence that the bunch thickness was about 40 times larger than what had originally been expected (Fig. 7), assuming that the vertical dimensions of the beams were determined by recoil effects originating from the emission of the synchrotron radiation photons. Since the beam intensity decayed rather quickly once the fill was over, we had to rush to install the detectors to look for secondary particles produced in $e^+ \cdot e^-$ collisions in order to make the best of the ring luminosity.

Originally, evidence of beam-beam collisions was sought in the form of pairs of high energy γ rays being produced by $e^+ - e^-$ annihilations (Fig. 2a). These γ rays were expected to come out of the ring back to back, and two lead glass Cerenkov counters were disposed in a way to detect them in coincidence. These two lead glass blocks, 15 cm in diameter and 25 cm long, were quite beautiful. Each one sat on top of some kind of a mechanical tower, more than 2 meters high so that their height would match the one of the AdA beam. Originally, these detectors were kept in the AdA hall during injection, to save time in their installation close to the interaction region, once the beams were stored. We did not realize that the ring magnetic field had a sweeping effect on the Linac beam, thus sending high energy particles in the Cerenkov counters. Radiation turned the beautiful blocks as black as coal. Fortunately, their transparency was recovered by baking them very very slowly up to 150°C.



(a) (b) (c)

Figure 7: (a) Optical picture of the AdA electron beam obtained by focussing the synchrotron light emitted by the stored particles. (b) Horizontal and vertical profiles of the beam spot shown in (a). Note that the narrower profile, which corresponds to the vertical beam dimension, is dominated by diffraction effects.

Following this mishap, the two dectectors were kept outside the AdA hall during injection. Once AdA was filled with electrons and positrons, the detectors were wheeled next to the ring as quickly as possible. Unfortunately, the only path available had a slanted section, and the unavoidable happened: one night, one of the Cerenkov detectors tipped over and broke Pierre Marin's foot. After that, the whole mechanical structure was redesigned and we had to resort to hoisting these heavy detectors with old fashioned chains and pulleys.

I also remember that, to begin with, the electronic signals were sent to a 4-track fast oscilloscope, an unusual apparatus, brought especially from Frascati, and the pictures of the cathodic ray signals were taken with a polaroid camera – an important tool in experimental physics at the time.

6 The choice of a new physic process

Because the size of the bunches appeared to be much larger than originally expected, one had to resort to a new physical process to reveal collisions between electrons and positrons. To solve this new problem, a new idea was put forth, namely to look at single bremsstrahlung events rather than two gamma annihilations. In typical running conditions, the former process whose cross-section had been conveniently computed just that year (1964) by Altarelli and Bucella [8], has a probability to occur about 300 times larger than the latter reaction. Yet it turned out that identifying those photons emitted in $e^{+}-e^{-}$ collisions was not a trivial task since the photons to be detected were essentially indistinguishable from those produced in beam gas collisions. A comparatively long series of measurements and checks had to be carried out with varied experimental conditions in order to disentangle the two contributions.

7 First evidence for beam-beam collisions

One of the tricks employed for this purpose was to vary the size of the stored bunches with the use of a small rotated quadrupole installed on AdA following a suggestion made by Carlo Bernadini. Aiming the detectors at a point along the beam orbit off the interaction region was another way of cross-checking the origin of the photons that were detected. By mid 1964, enough data had been collected to come to a positive conclusion concerning beam-beam collisions. For the first time, evidence was produced that counter-rotating bunches of electrons and positrons do collide in a storage ring. The beam height was thus measured and it was confirmed that it was about 40 times larger than the one computed by taking only synchrotron radiation into account (a few microns).

The peak luminosity reached with AdA at Orsay was on the order of 10^{25} cm^{-2} s^{-1}. It is interesting to note that, despite this modest value of the luminosity, Bruno Touschek thought of performing an energy scan with AdA [10], just in case the photon form factor would reveal some surprise. As we all know, such a hypothesis turned out to be true, but at much higher energies.

8 The outcome of experimentation with AdA

A number of accelerator physics questions raised by storage rings had been tackled with AdA, in particular, effects resulting from the beam interactions with the residual gas (bremsstrahlung, scattering on the atomic electrons [4]), quantum fluctuations and RF lifetime, vertical/horizontal coupling of betatron oscillations, Touschek effect. Single bremsstrahlung in beam-beam interactions was observed for the first time. A detailed account of these observations was published in the 1964 December issue of Il Nuovo Cimento [5].

None of the basic ideas underlying the concept of storage rings was found to be wrong. The Groups which, at the time, were in the process of building rings much larger than AdA could proceed with confidence. This was the case in particular of ADONE [6] and ACO [7].

9 Early times of the ACO programme

For obvious reasons, the physicists and engineers from Orsay missed a number of important developments made during the construction period of AdA in Frascati [1]. These were essentially the magnet elegantly designed by G. Ghigo, the ultrahigh vacuum chamber of G. Corazza – a true achievement at the time –, the RF cavity and transmitter built by M. Puglisi which never failed while at Orsay. Contrary to the above, some of the findings with AdA had a direct impact on ACO:

- Firstly, concerning the Touschek effect, it was a great relief to realize that, for both ACO and ADONE, the large energy acceptance of the new strong focussing, separated function optics ensured a much higher beam lifetime than the one observed with AdA.
- Secondly, horizontal-vertical coupling of betatron oscillations was used at full extent in ACO for maximizing the luminosity on a coupling resonance.

Even more essential to us, was the idea that storage rings (or colliders) were not static devices, but systems open to the discovery and the investigation of new phenomena: head-tail instability, bunch lengthening, multiple Touschek effect, beam-beam incoherent scattering, instability bands in the betatron frequency diagram, ion trapping are examples of effects which soon came to the forefront of storage ring physics. Of course, all these studies needed the prolonged efforts of a large group of physicists and accelerator engineers.

Besides, the Orsay team, as well as those working on other projects, had to develop a proper know-how concerning the many technological aspects of high intensity colliders: high positron flux, large injection efficiency, synchrotron radiation absorption, electrostatic separation of electron and positron orbits, fine control of the optics during energy ramping etc.

At the same time, efforts were made [9] by groups of physicists who, over a period of ten years, built more and more sophisticated detectors, well adapted to the specific features of collider interaction regions.

10 AdA in perspective

Coming back to this period when AdA was at Orsay, one of the nice features of our activity was the rapid reaction of the Italian team to adapt the programme and modify the ring or the detectors to take into account the new findings. Another one was the constant interplay between observation and theoretical interpretation, where Bruno Touschek played a major role. Quite a lot of physics was thus covered in a comparatively short time. All these results were obtained in less than two years of experimentation.

Today, about 35 years later, one may put in perspective these early steps with the extraordinary development of e^+- e^- machines that have followed. They have lead to the achievement of very high energy beams with LEP and to the design of very high luminosity machines required by meson factories like DAΦNE. A visit to DAΦNE (Fig. 8) is enlightening in this respect. Indeed, DAΦNE is a machine whose energy is only 2 1/2 times the one of AdA but which integrates all of the state-of-the-art technology needed to carry out the very demanding CP violation programme (the luminosity aimed at with DAΦNE is $\sim 10^8$ higher than the one reached with AdA).
Thus we have witnessed the impressive advances of e^+- e^- machines since the early sixties. And we shall remember that at the origin of this scientific breakthrough, and during the following two decades of beautiful and rich developments, there was the imagination and enthusiasm of a brilliant physicist, Bruno Touschek.

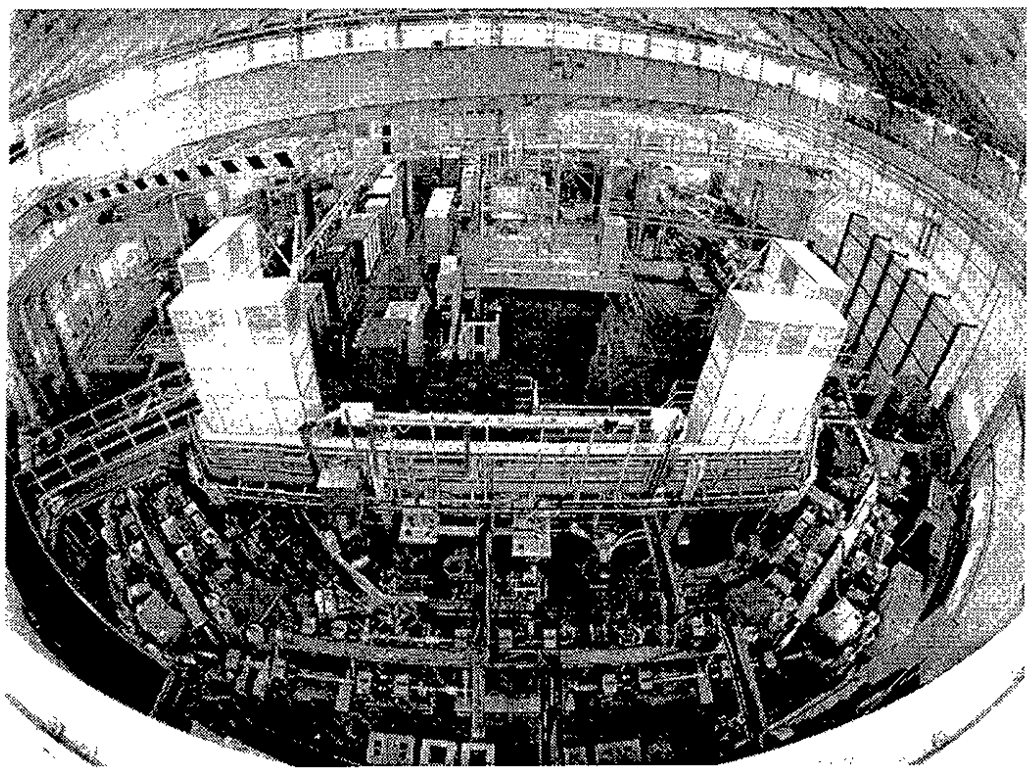


Figure 8: A photograph of DAΦNE taken in 1998.

Acknowledgements

It is a pleasure for me to thank Pierre Marin for his help in bringing back these reminiscences.

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